Modeling the H_2O and CO_2 Outgassing of Comet 67P/C-G

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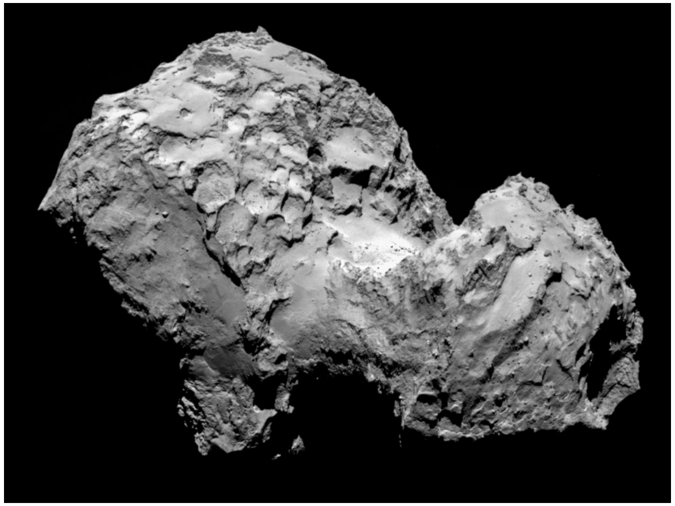
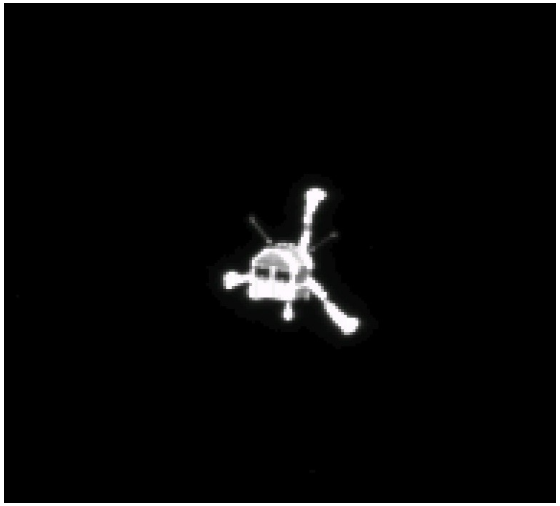
Outline

- What I do and why
- South vs. North: Fresh(er) vs. old(er) material
- The thermophysical model NIMBUS
- Reproducing the water and carbon dioxide production rates
- Conclusions

What I do and why





The ESA mission *Rosetta/Philae* to comet 67P/Churyumov-Gerasimenko (at the comet Aug 2014 – Sep 2016):

The nucleus surface and the coma are well-known.

The nucleus interior remains largely unknown.

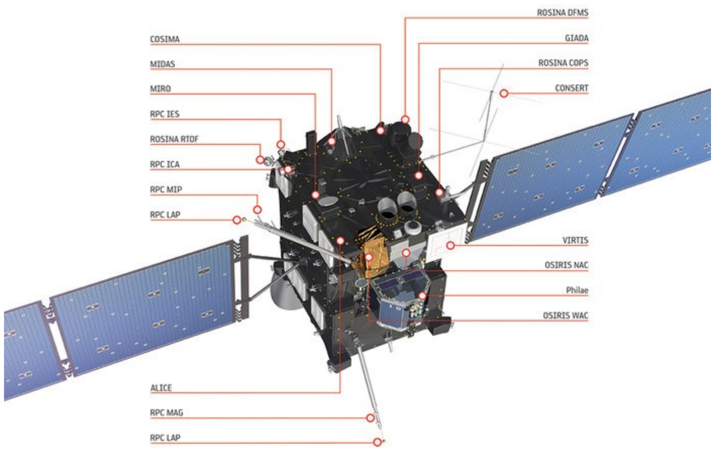
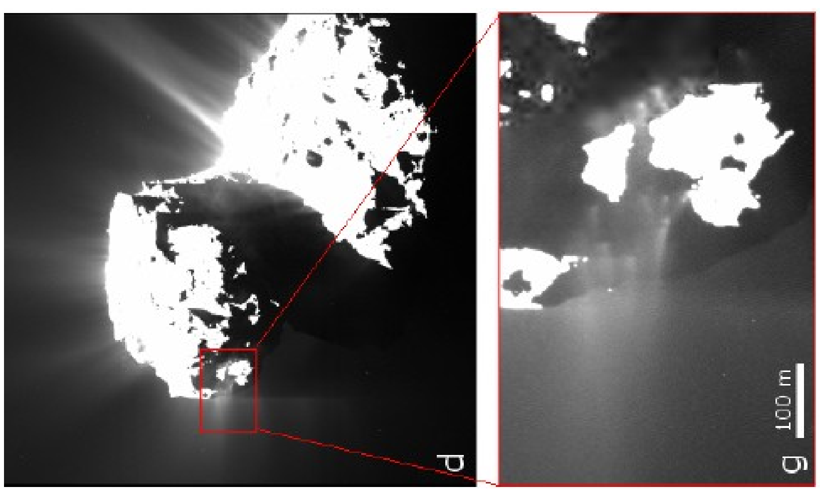


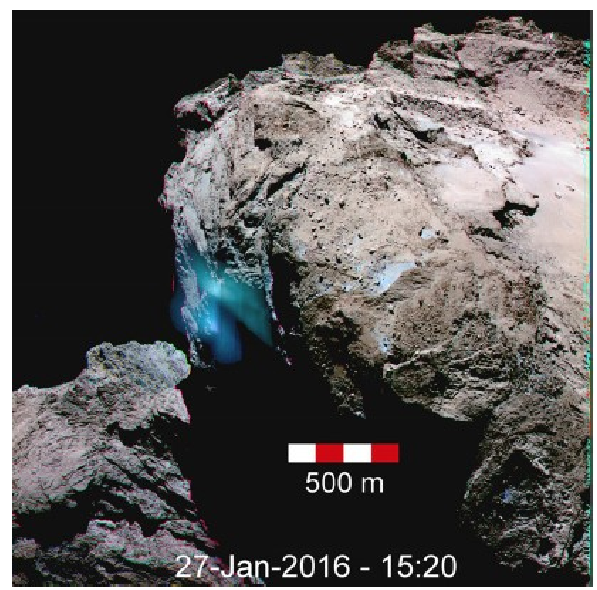
Image credits: ESA/Rosetta/MPS for OSIRIS Team MPS/UPD/LAM/IAA/SSO/INTA/UPM/DASP/IDA

Image credit: ESA

What I do and why

- What is dust/ice mass ratio of the interior?
- At what depth is water ice located?
- At what depth is CO_2 ice located?
- Local forces and torques due to outgassing?





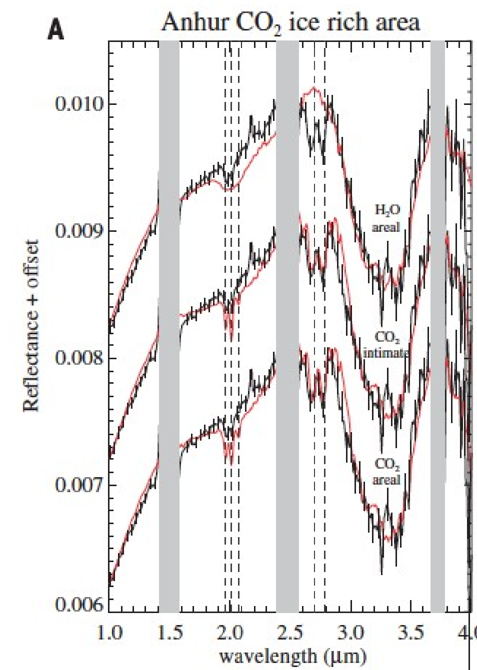


Image credits:
Left: Shi *et al.* (2017, *MNRAS* **469**, S93)
Center: Fornasier *et al.* (2017, *A&A* **586**, A7)
Right: Filacchione *et al.* (2016, *Science* **354**, 1563)

What I do and why

- Assume certain physical and chemical properties of the nucleus
- Perform thermophysical modeling
  - Solve the coupled differential equations governing heat and gas diffusion
  - Local production rates (vs. latitude and time) physically consistent with prevailing illumination conditions
- Compare modeled and observed total production rate curves
- Adjust assumptions until the model reproduces the data

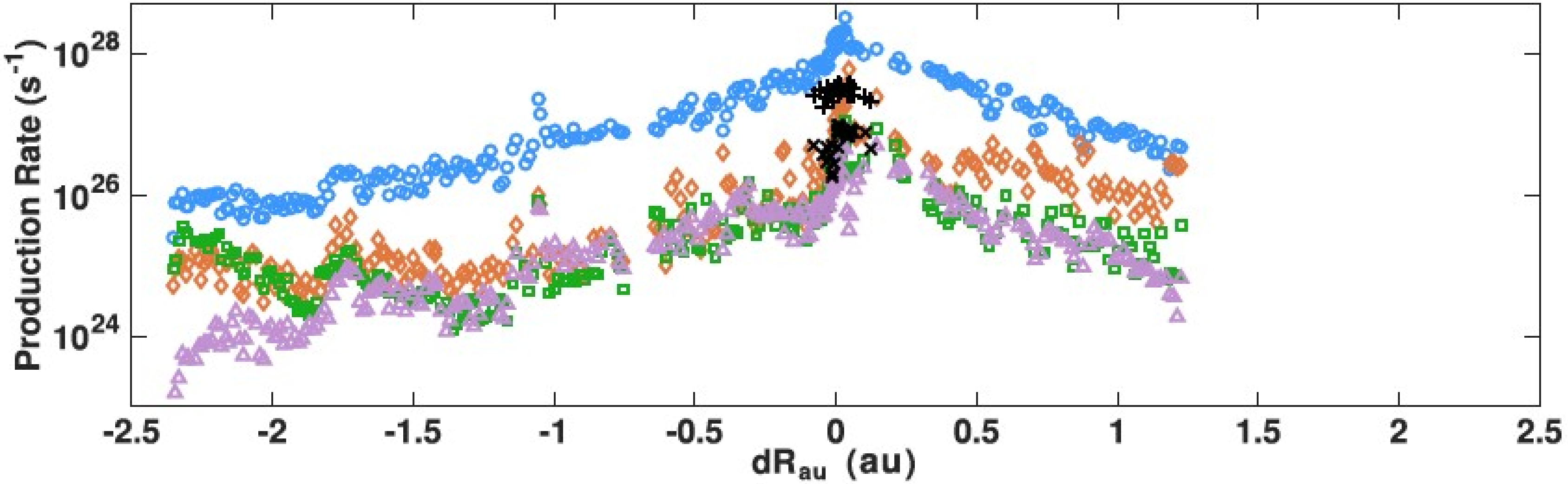
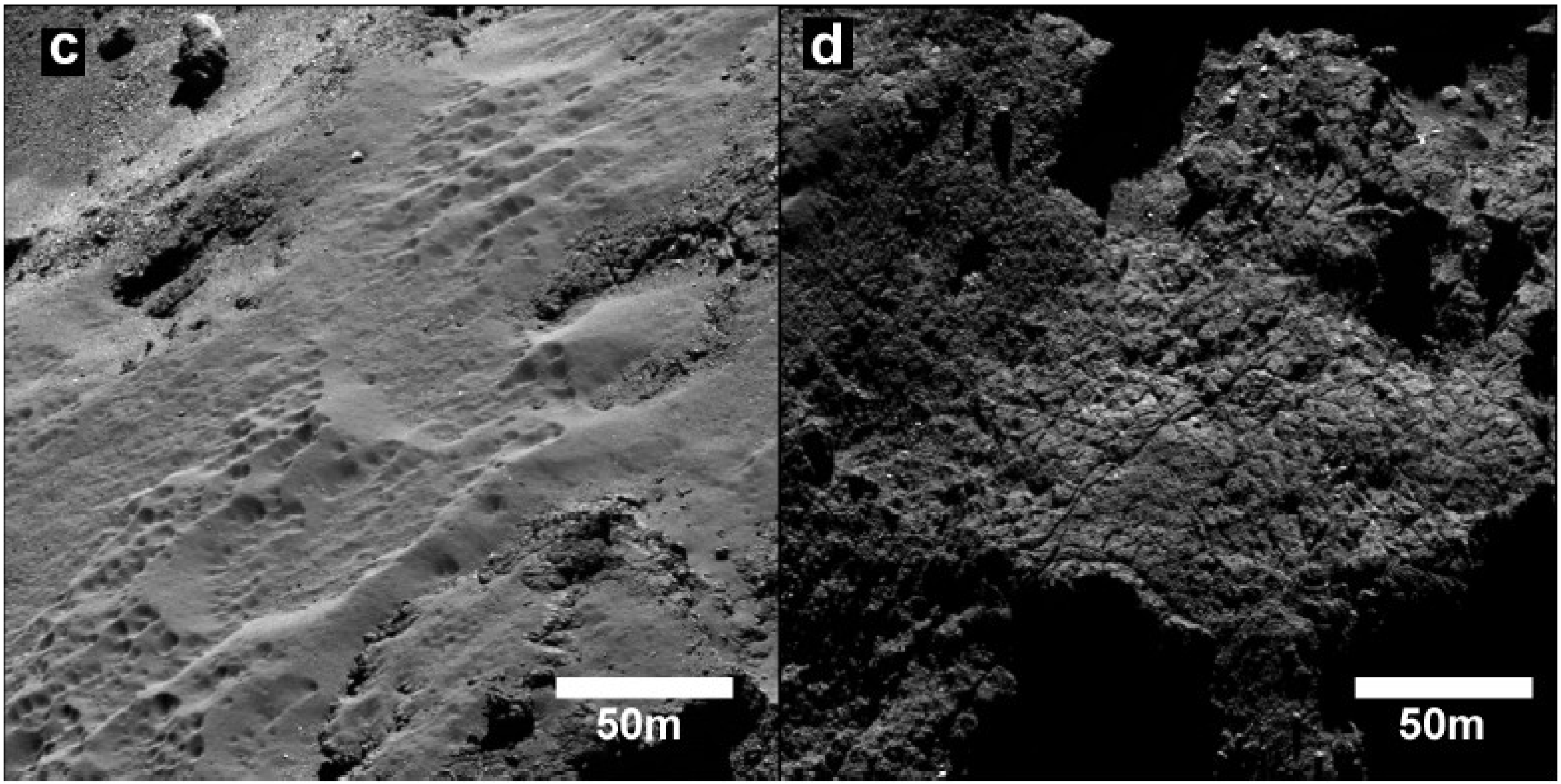


Image credits: Fougere *et al.* (2016 *MNRAS* **462**, S156)

South vs. North:
Two very different terrain types on 67P/C-G



North:
Old(er) smooth terrain

South:
Fresh(er): consolidated terrain

Image credits: El-Maarry *et al.* (2015 *A&A* **583**, A26)

South vs. North

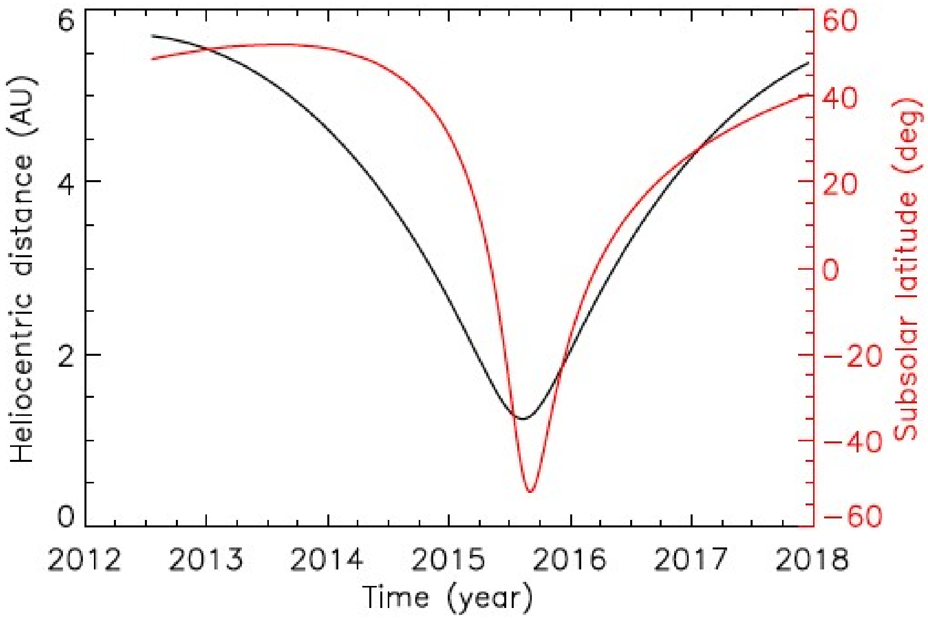


Image credit: Keller *et al.* (2015, *A&A* **583**, A34)

PERIHELION

- The southern hemisphere
  - Strong illumination
  - High dust and gas production rates
- The northern hemisphere
  - Polar night
  - Recipient of airfall material

The south: consolidated terrain

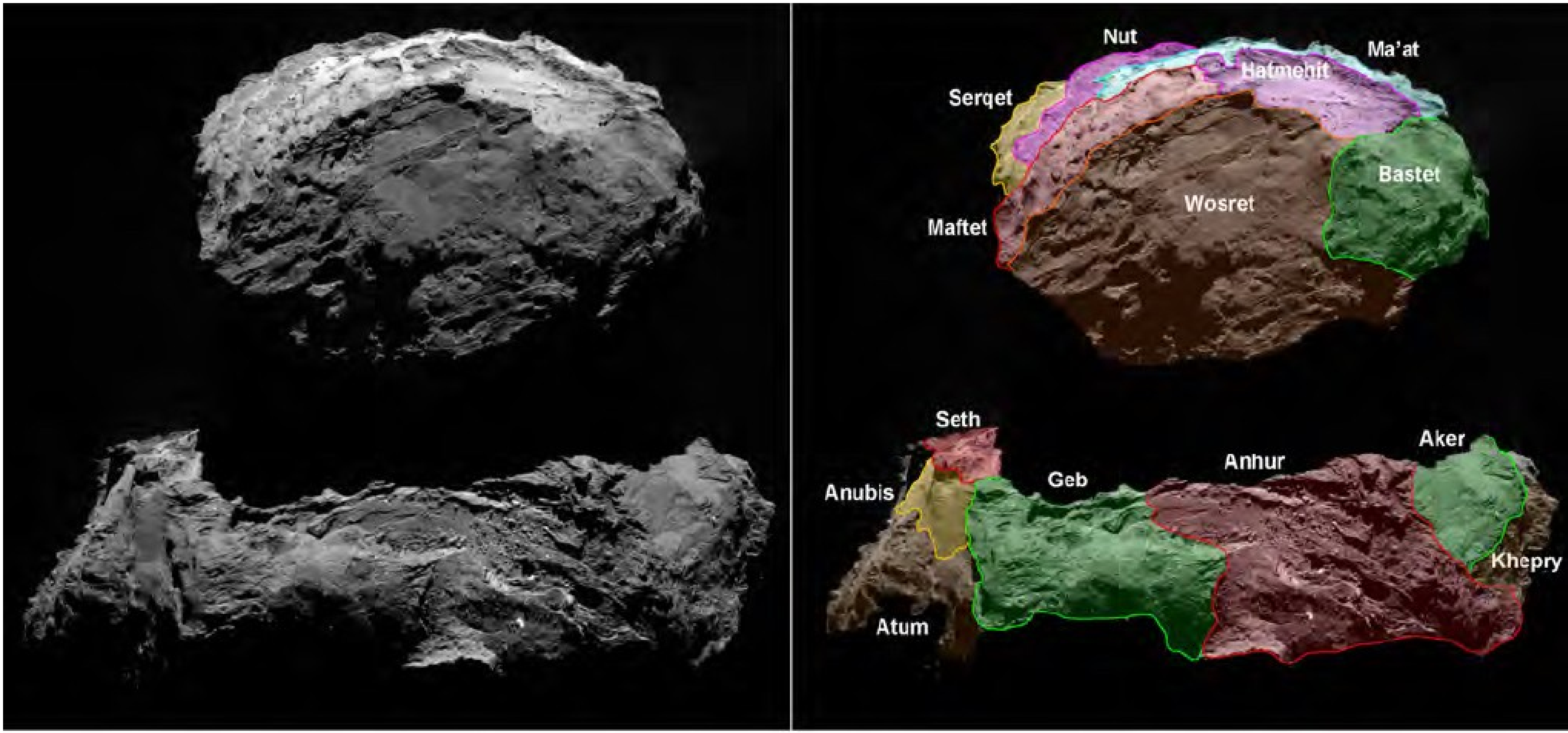
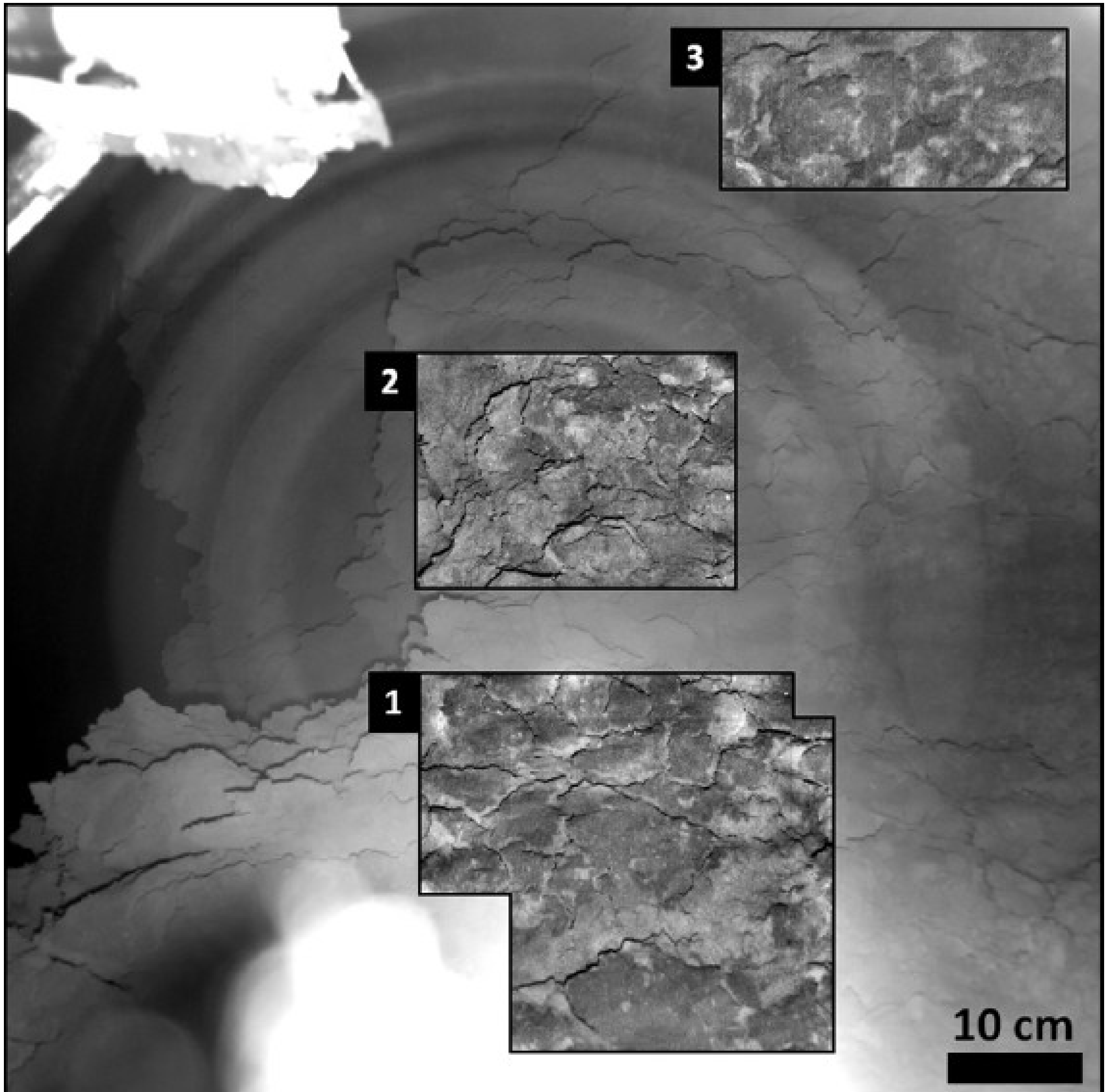
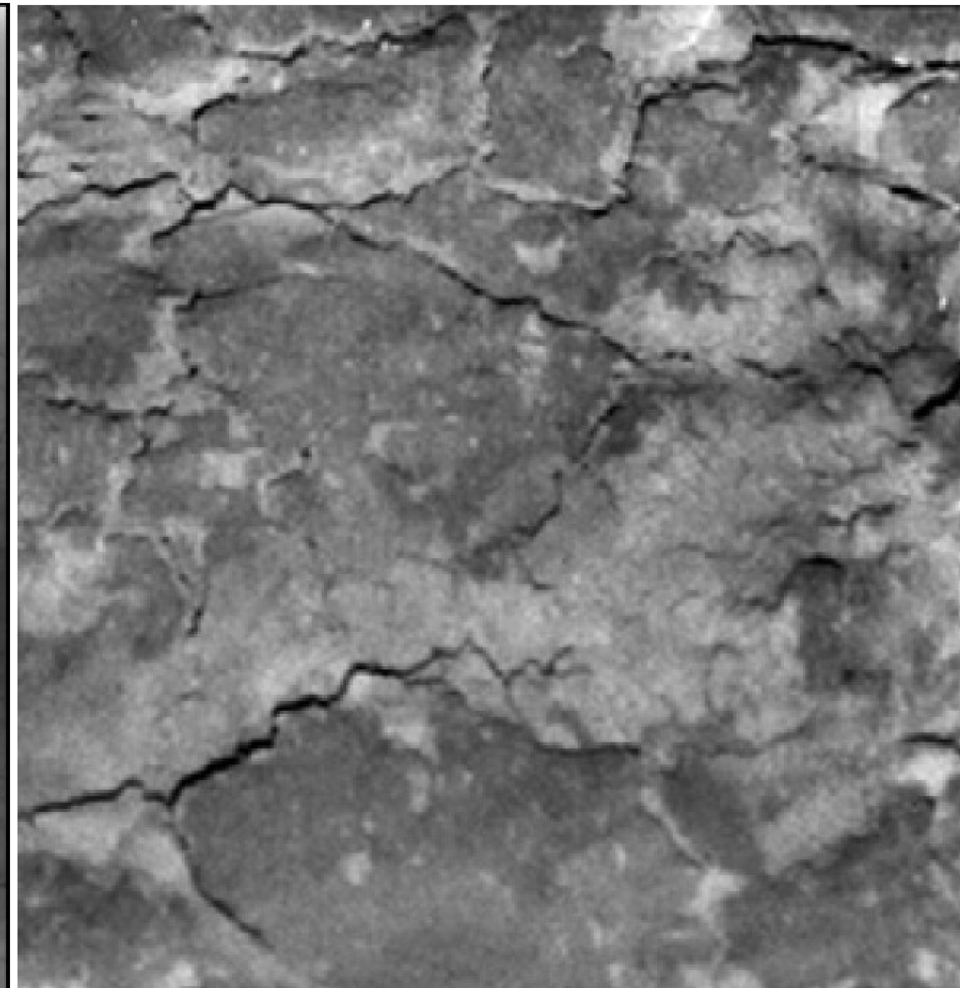


Image credits: El-Maarry *et al.* (2016 *A&A* **593**, A110)

The south: consolidated terrain

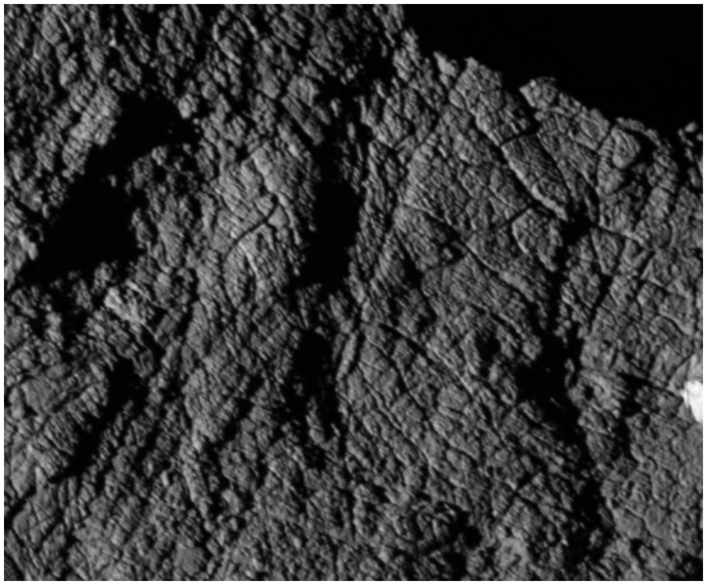




Cracked consolidated material at Abydos – final resting place of Philae

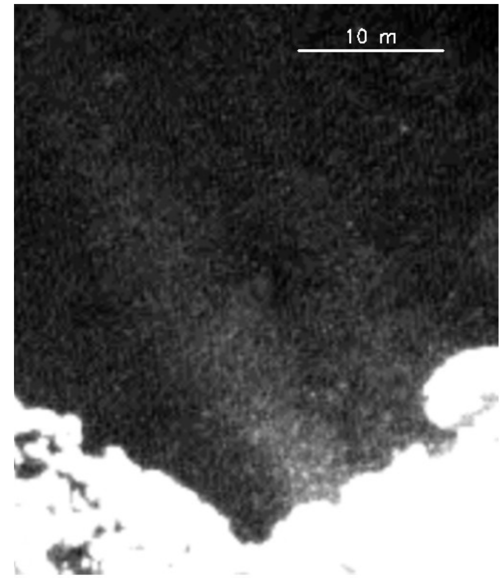
Image credits: Schröder *et al.* (2017, *Icarus* **285**, 263)

South to north transport



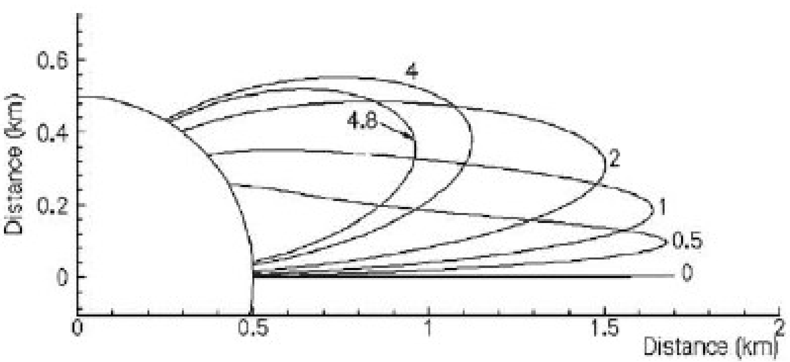
Cracking of consolidated material

⇒



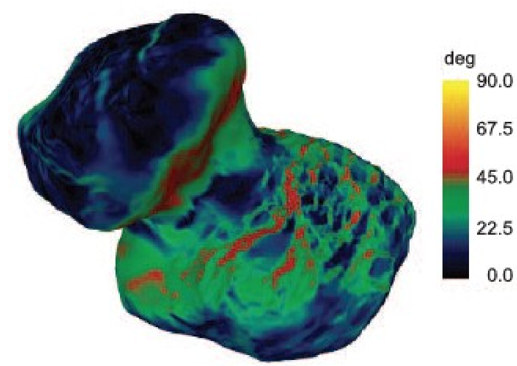
Lift-off of cm-dm chunks

⇒



Ballistic flight and fall back

⇒

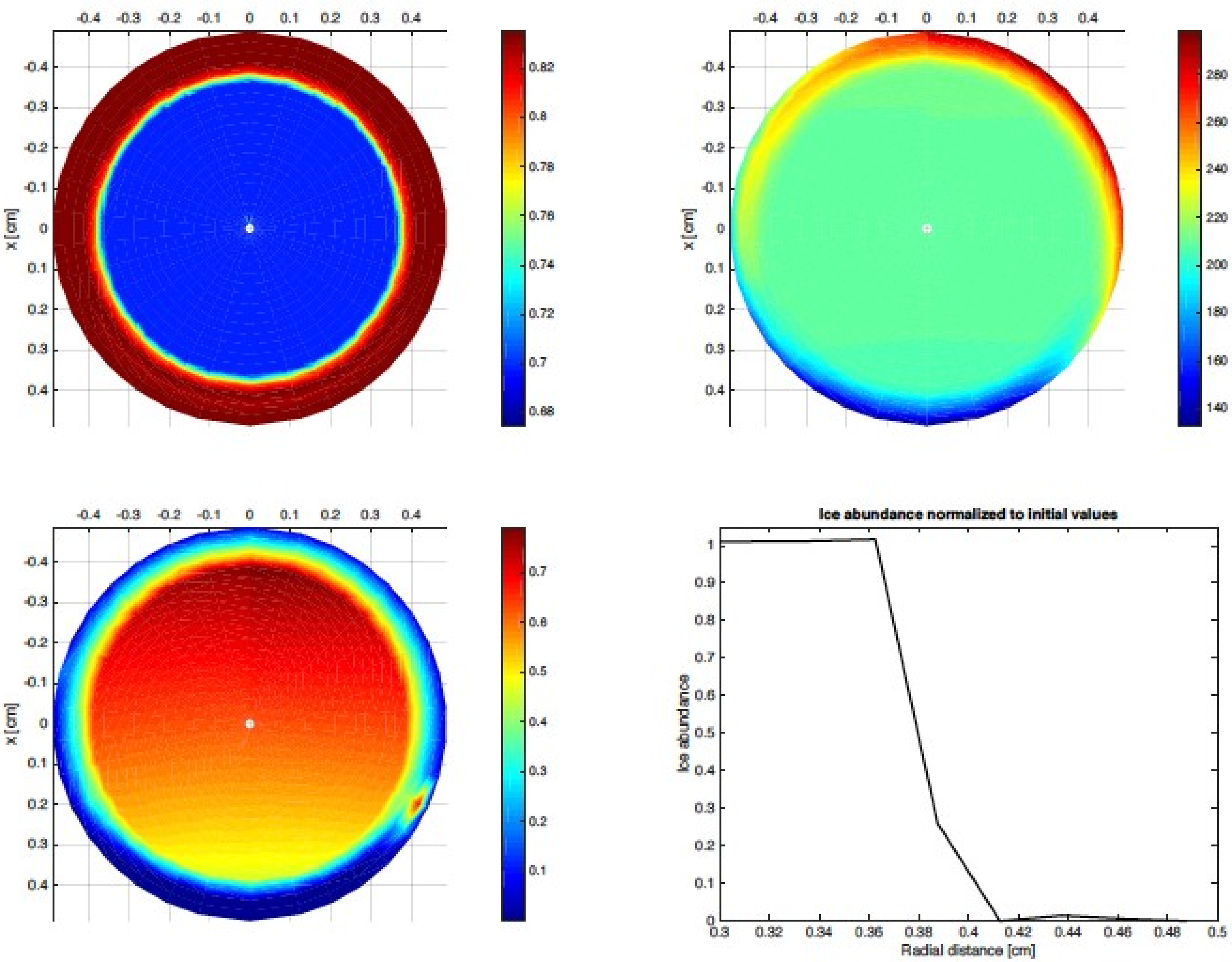


Deposition on level surfaces

Image credits: UL: El-Maarry *et al.* (2015, *GRL* **42**, 5170); UR: Thomas *et al.* (2015, *A&A* **583**, A17); LL: Crifo *et al.* (2005, *Icarus* **176**, 192); LR: Sierks *et al.* (2014, *Science* **347**, aaa1044)

South to north transport

NIMBUS: D=1 cm chunk after 11.4 hours flight



Ice loss during 12h coma flight

Chunks: 70% porosity, d/i=4, 5% CO_2 rel. H_2O by number

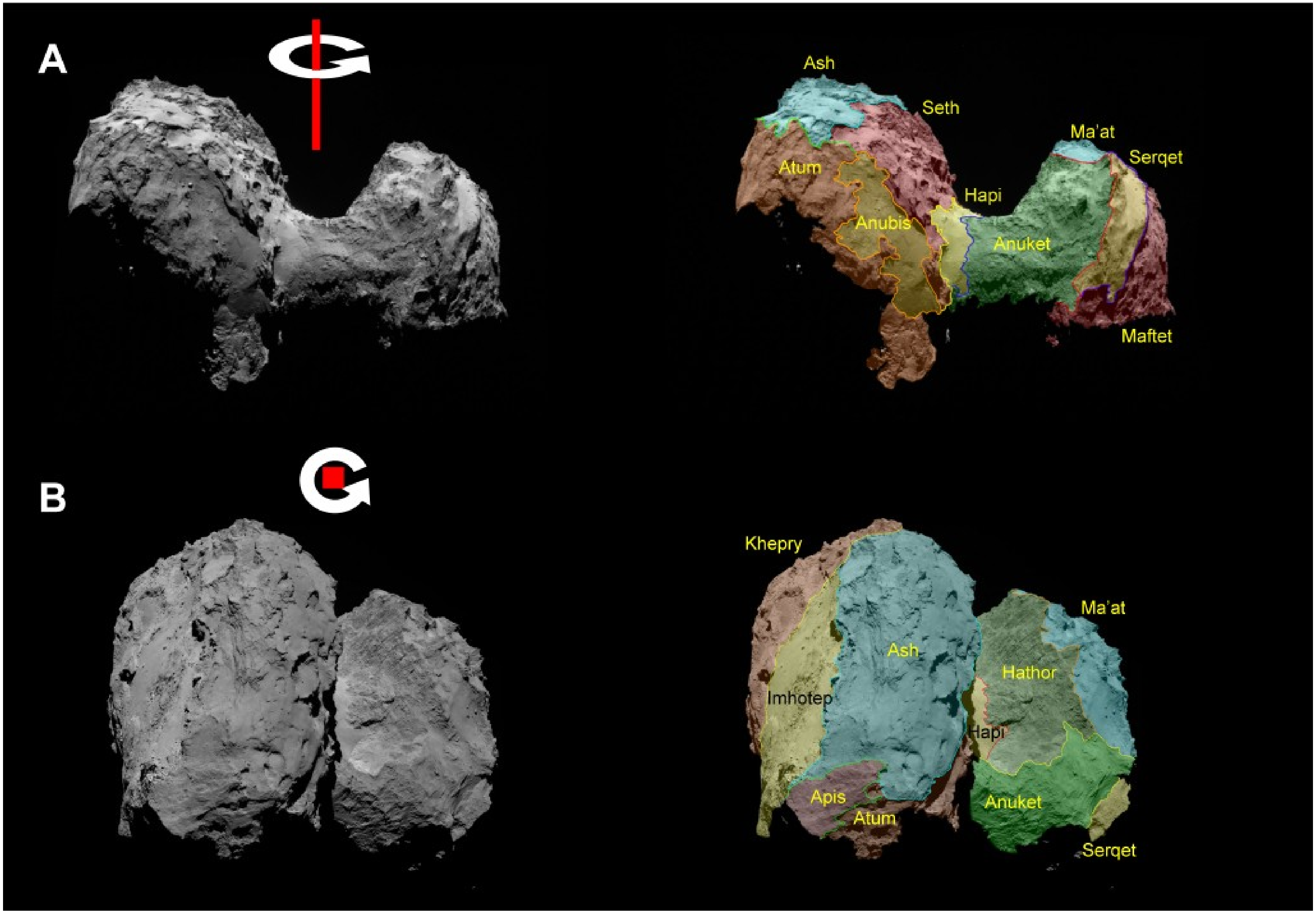
Water:
D=1cm: 56% lost
D=10 cm: 4.8% lost

Carbon dioxide:
D=10 cm: all CO_2 lost in 2h

Airfall material likely rich in water ice but poor in CO_2!

Image credits: Davidsson *et al.* In preparation.

The north: smooth terrain



<u>Smooth plains</u>

Hapi
Anubis
Imhotep

<u>Dust-covered consolidated terrain</u>

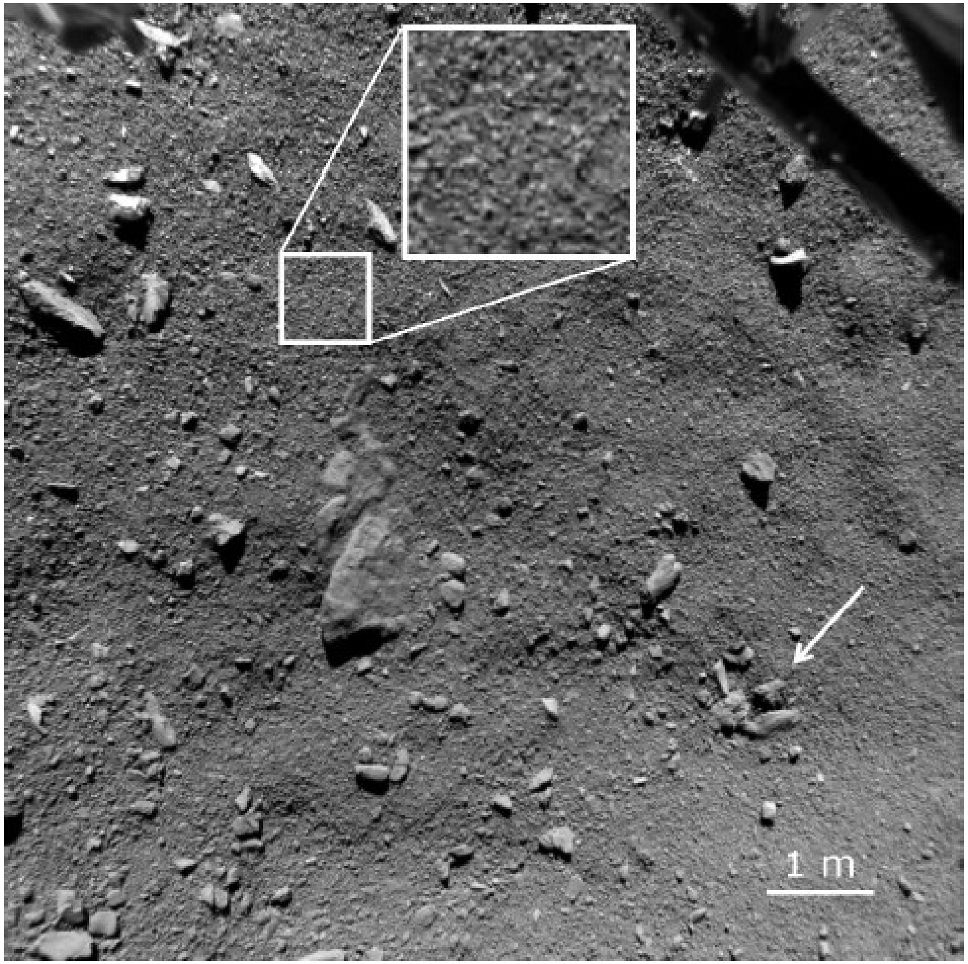
Seth
Ash
Ma’at
Maftet

<u>Consolidated</u>

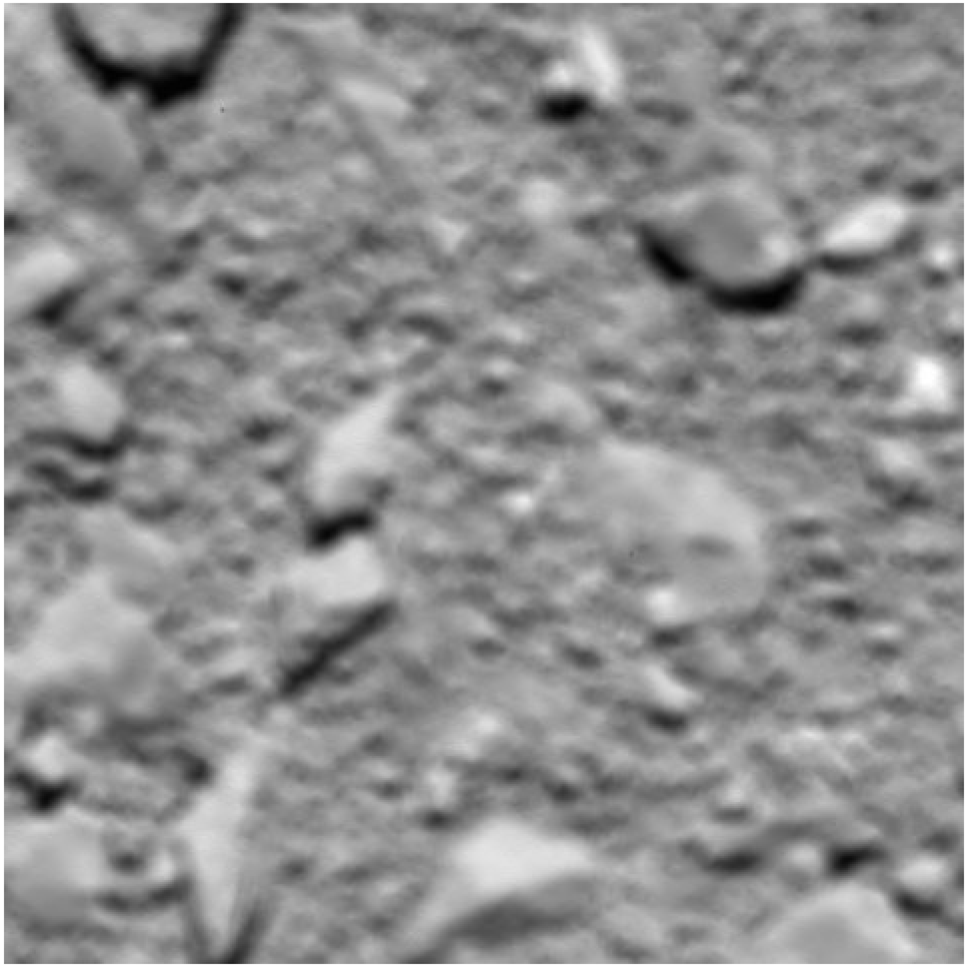
Atum
Apis

Image credits: El-Maarry *et al.* (2015 *A&A* **583**, A26)

The north: smooth terrain



Agilkia at 0.95 m px^{-1} resolution (ROLIS)
(Image credits: Mottola *et al.* 2015, *Science* **349**, aab0232)



Sais at 0.002 m px^{-1} resolution (OSIRIS)
(Image credits: ESA/Rosetta/MPS for OSIRIS Team MPS/UPD/LAM/IAA/SSO/INTA/UPM/DASP/IDA)

South vs. North

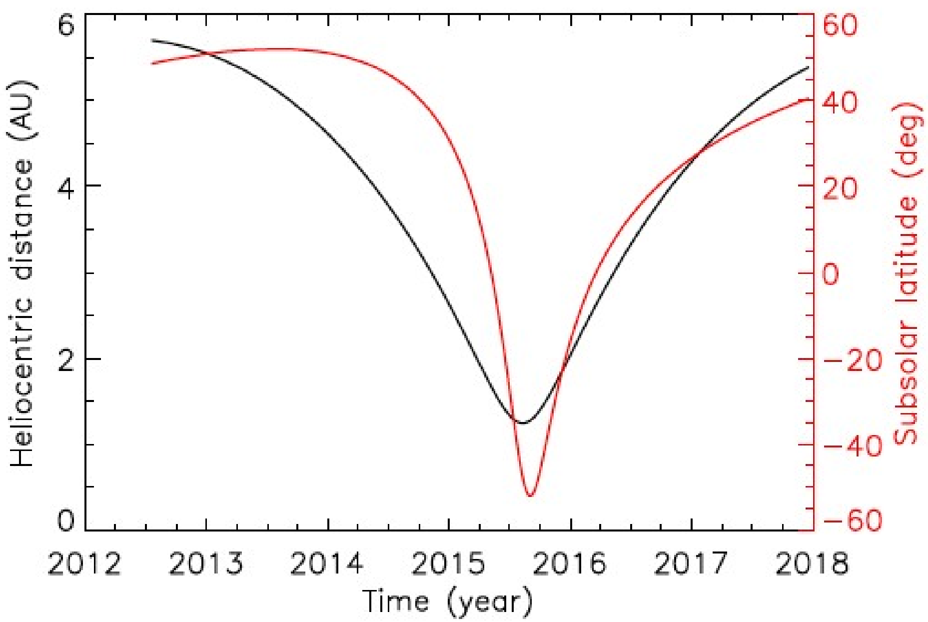


Image credit: Keller *et al.* (2015, *A&A* **583**, A34)

APHELION

- The southern hemisphere
  - Polar night
- The northern hemisphere
  - Illuminated by the Sun
  - Airfall material is sublimating
  - Rosetta met 67P like this (Aug 2014).
  - Shifts to southern dominance around inbound equinox (May 2015)

NIMBUS

Numerical Icy Minor Body evolUtion Simulator

Energy conservation equation:

Energy change | Radial heat conduction | Latitudinal heat conduction

$$\rho c(T)\frac{\partial T}{\partial t} = \frac{1}{r^2}\frac{\partial}{\partial r}\left(\kappa(\psi,\,T)r^2\frac{\partial T}{\partial r}\right) + \frac{1}{r\sin l}\frac{\partial}{\partial l}\left(\kappa(\psi,\,T)\frac{\sin l}{r}\frac{\partial T}{\partial l}\right)$$

$$-\sum_{\imath=4}^{n_{\mathrm{sp}}} q_\imath(p_\imath,\,T)\mathcal{L}_\imath(T) + \sum_{\imath=2}^{n_{\mathrm{sp}}}\sum_{\jmath=5}^{n_{\mathrm{sp}}}\left(q'_\imath(T)\left\{H_\imath - F_{\imath\jmath}\mathcal{L}_\jmath(T)\right\}\right) - \sum_{\imath=4}^{n_{\mathrm{sp}}} g_\imath\left(\Phi_\imath\frac{\partial T}{\partial r} - \frac{\Psi_\imath}{r}\frac{\partial T}{\partial l}\right) + R_*$$

Sublimation/Condensation | Crystallization/Segregation | Advection (radial, latitudinal) | Radiogenic heating

Energy conservation upper boundary condition:

$$\frac{S_\odot(1-A)\mu(l,t)}{r_{\mathrm{h}}^2} = \sigma\varepsilon T_{\mathrm{surf}}^4 - \kappa\frac{\partial T}{\partial r}\bigg|_{r=R_{\mathrm{n}}}$$

Solar illumination | Thermal reradiation | Radial heat conduction

Gas mass conservation equation (species ı):

$$\psi m_\imath\frac{\partial n_\imath}{\partial t} = -\frac{1}{r^2}\frac{\partial}{\partial r}\left(r^2\Phi_\imath\right) - \frac{1}{r\sin l}\frac{\partial}{\partial l}\left(\Psi_\imath\sin l\right) + q_\imath(p_\imath,\,T) + \sum_{\jmath=2}^{n_{\mathrm{sp}}} F_{\jmath,\imath}q'_\jmath(p_\jmath,\,T)$$

Gas mass change | Radial gas diffusion | Latitudinal gas diffusion | Sublimation/ Condensation | Crystallization/ Segregation

Ice mass conservation equation (species ı):

$$\frac{\partial\rho_\imath}{\partial t} = -q_\imath(p_\imath,\,T) + \tau_\imath$$

Ice mass change | Sublimation/ Condensation | Crystallization/ Cubic → hexagonal

Image credits: Davidsson *et al.* In preparation.

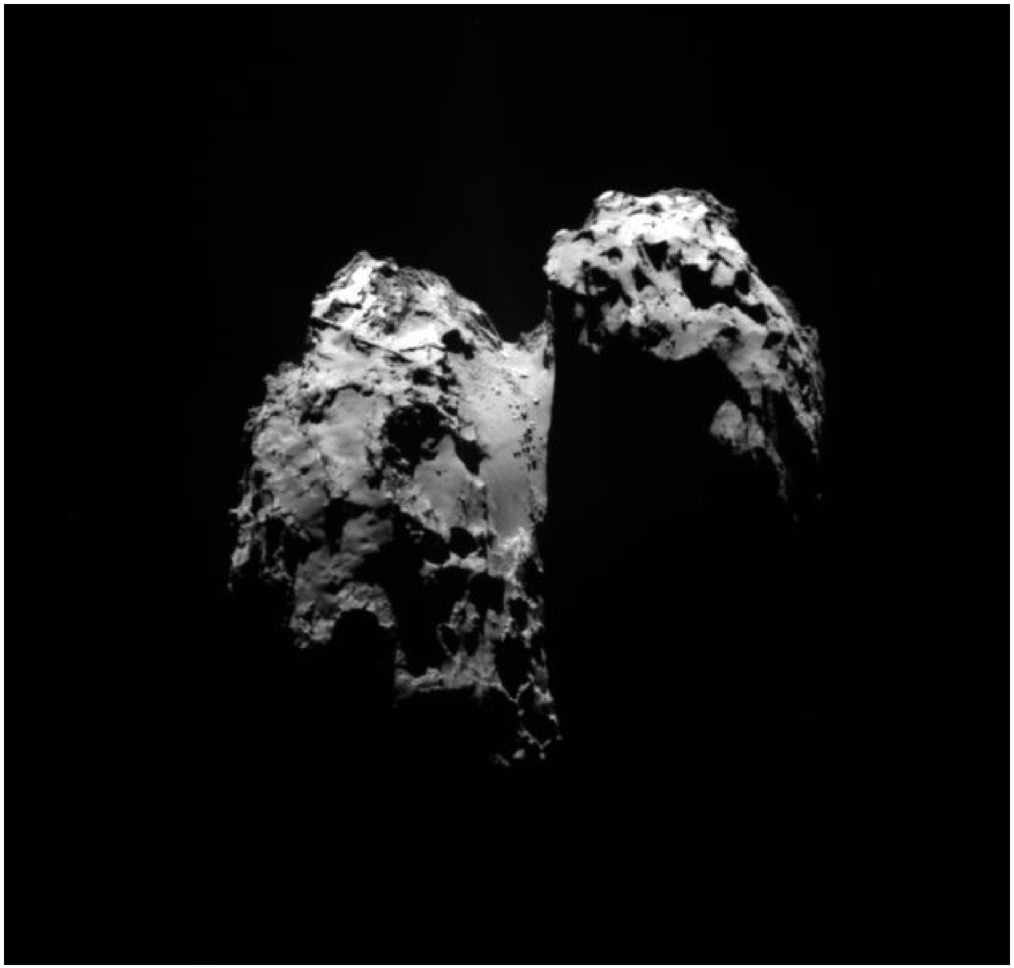
NIMBUS

- Laboratory measurements vs. temperature for dust (forsterite), H_2O, CO_2 used as much as possible:
- Heat capacity, heat conductivity, latent heat, saturation pressures etc
- Shoshany *et al.* (2001) porosity-correction for conductivity
- Few remaining free parameters: mass flux rate tube dimensions (length Δx=l, width r_p=r), abundances, initial depth of sublimation fronts

$$\bar{\phi}_{\mathrm{g}}(p, T) = -\frac{20\Delta x + 8\Delta x^2/r_{\mathrm{p}}}{20 + 19\Delta x/r_{\mathrm{p}} + 3(\Delta x/r_{\mathrm{p}})^2}\frac{\psi}{\xi^2} \times \sqrt{\frac{m_{\mathrm{H_2O}}}{2\pi k_{\mathrm{B}}}}\frac{\Delta(p/\sqrt{T})}{\Delta x}\hat{x},$$

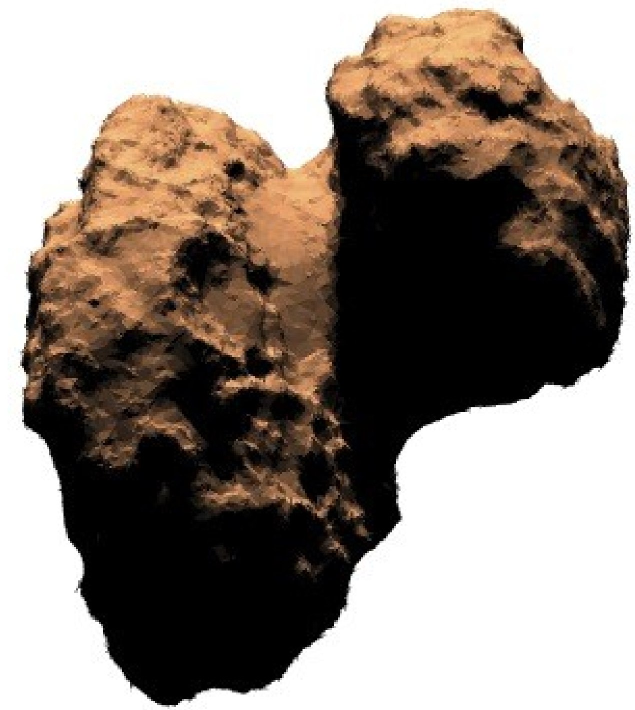
Image credits: Davidsson & Skorov (2002 *Icarus* **159**, 239)

Sphere ⇒ Shape model



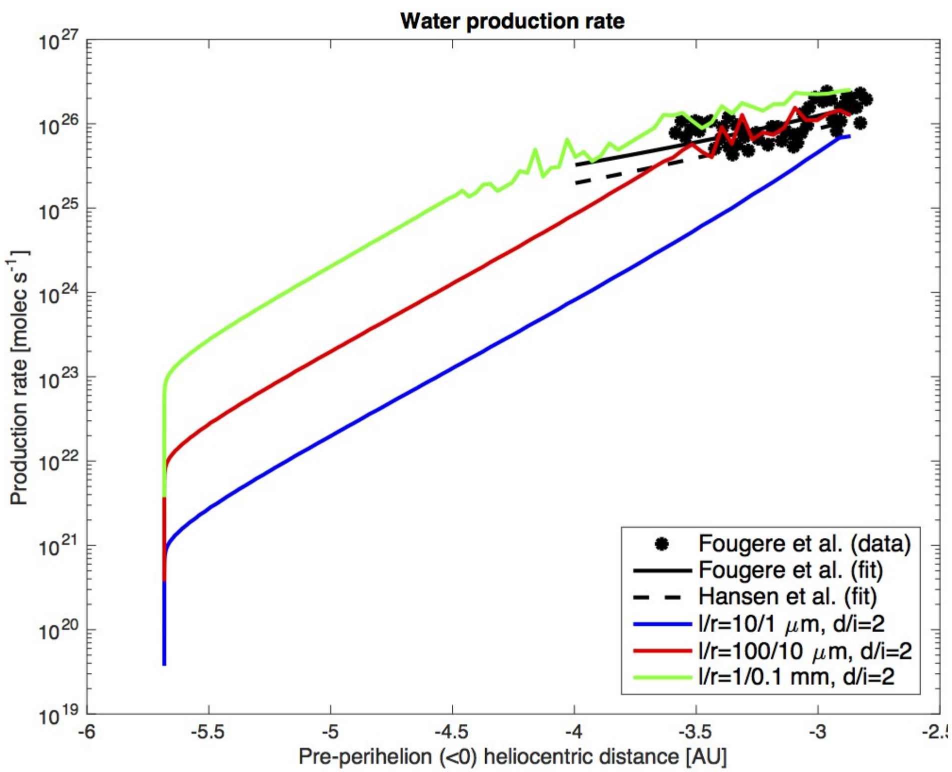
WAC image on Feb 9, 2015,
13:32:56.344 UTC

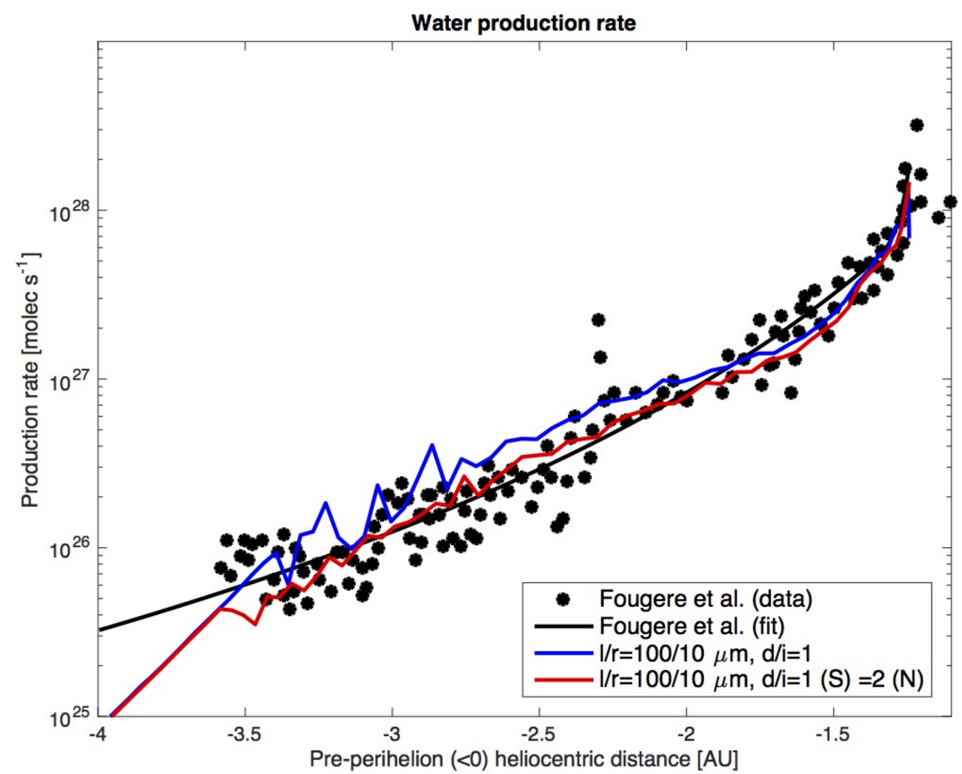
Image credits: ESA/Rosetta/MPS for OSIRIS Team
MPS/UPD/LAM/IAA/SSO/INTA/UPM/DASP/IDA



Synthetic image generated with the model of
Davidsson & Rickman (2014, *Icarus* **243**, 58-77)
Shape model SHAP5 version 1.5 (degraded)
by Jorda *et al.* (2016, *Icarus*, **277**, 257-278)

Water





Large distance: production rate Q_{H2O} insensitive to dust/ice mass ratio μ but sensitive to l/r

We find l/r=100/10 μm

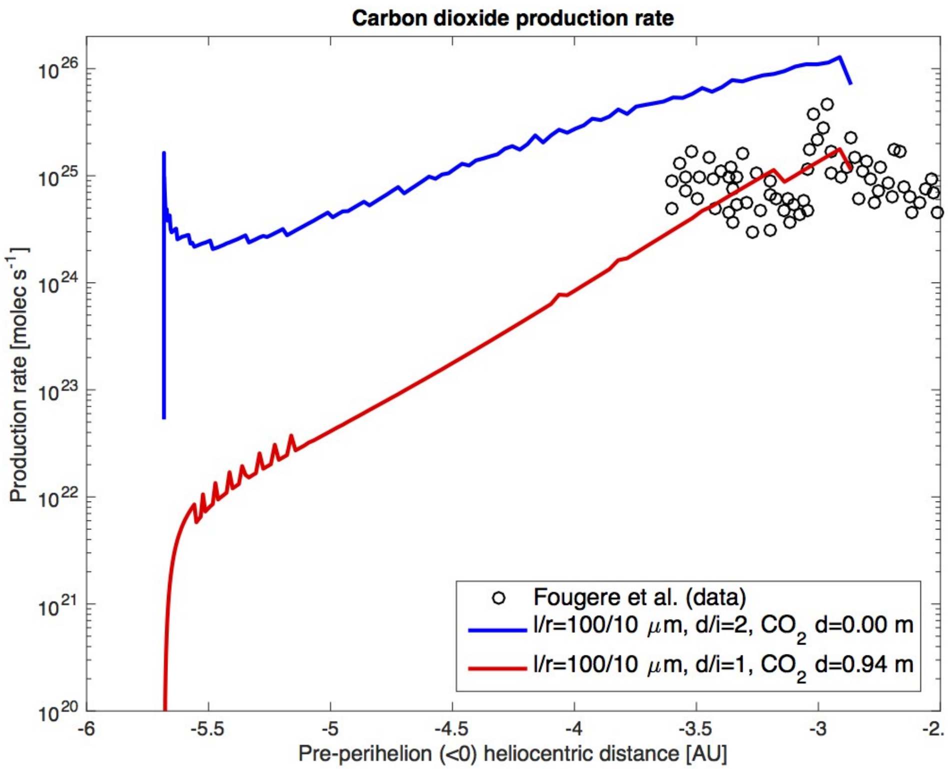
Perihelion: Q_{H2O} sensitive to μ but not l/r.

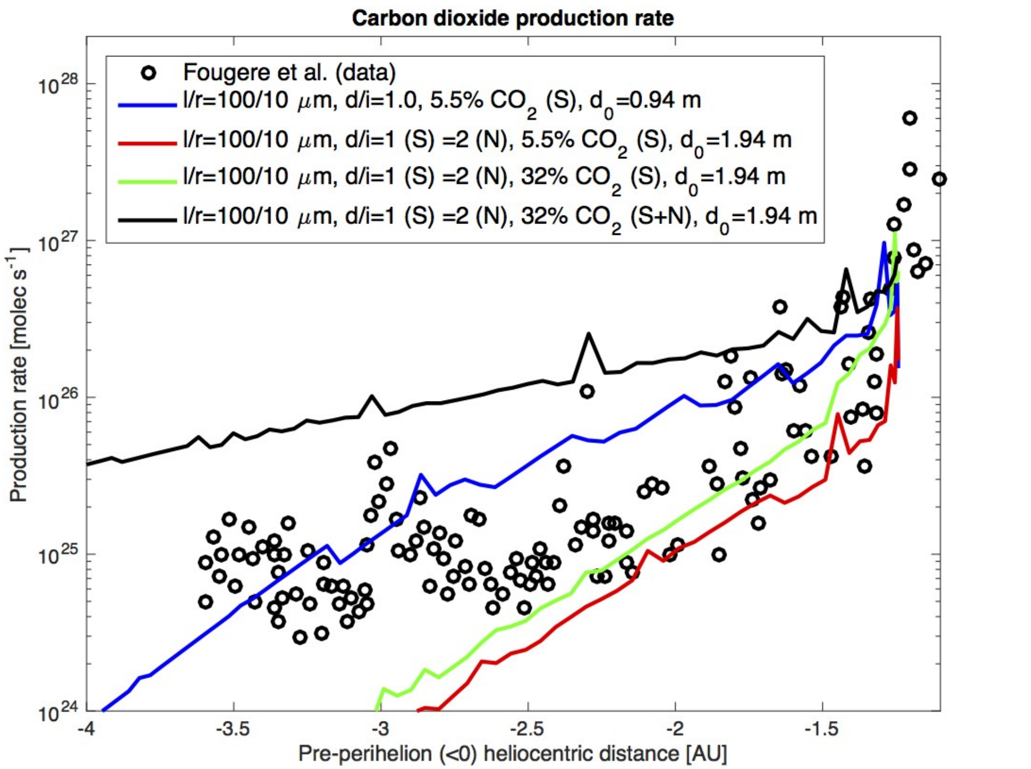
Simulation near perihelion suggests μ_S=1

From aphelion to perihelion: μ_N=1 (blue) too much; μ_N=2 (red) better

Image credits: Davidsson *et al.* In preparation.

Carbon dioxide: south only





CO_2 ice up to the surface (d=0) overshoots.

CO_2 sublimation front at d=0.94 m matches 3.5 AU observations...

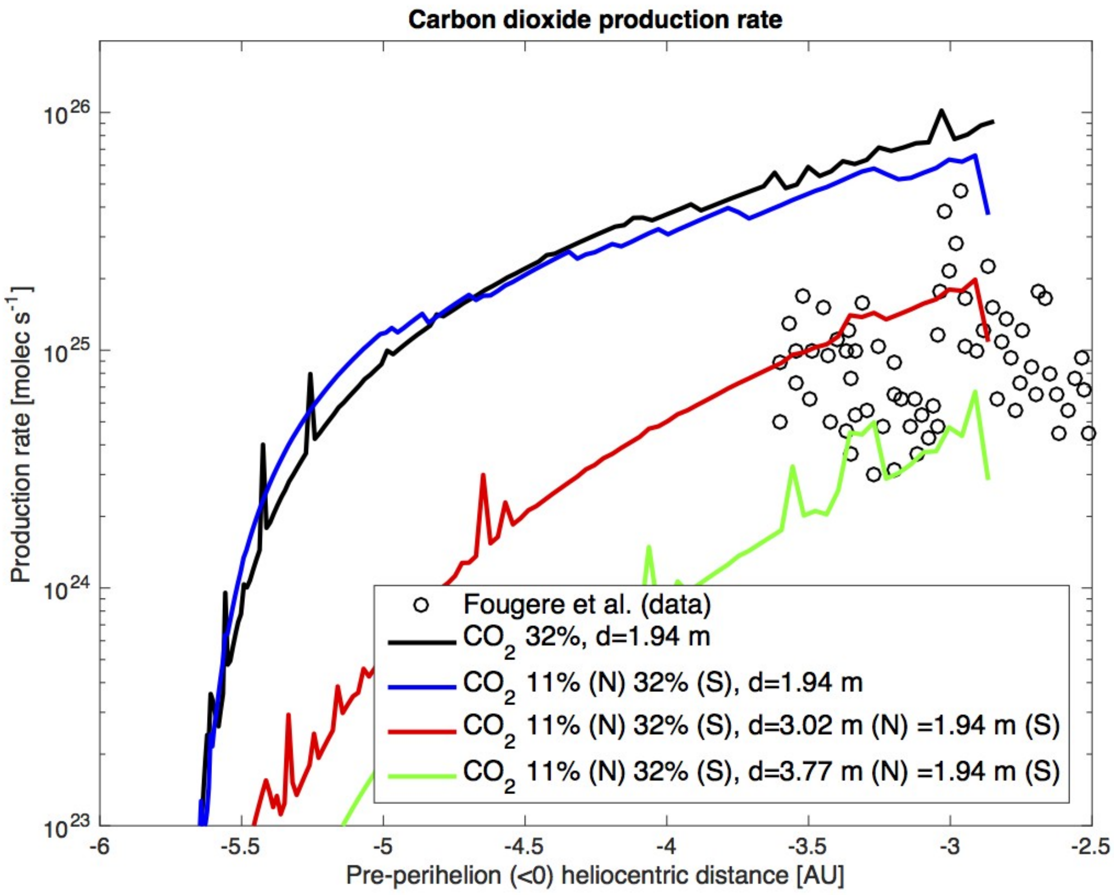
... but overshoots closer to the Sun (blue)

Increasing to d=1.94 m: reasonable at <2 AU, insensitive to (5-32%) CO_2 abund. (red/green)

Northern CO_2 source needed! But $d_N > d_S$ (black)!

Image credits: Davidsson *et al.* In preparation.

Carbon dioxide: north and south

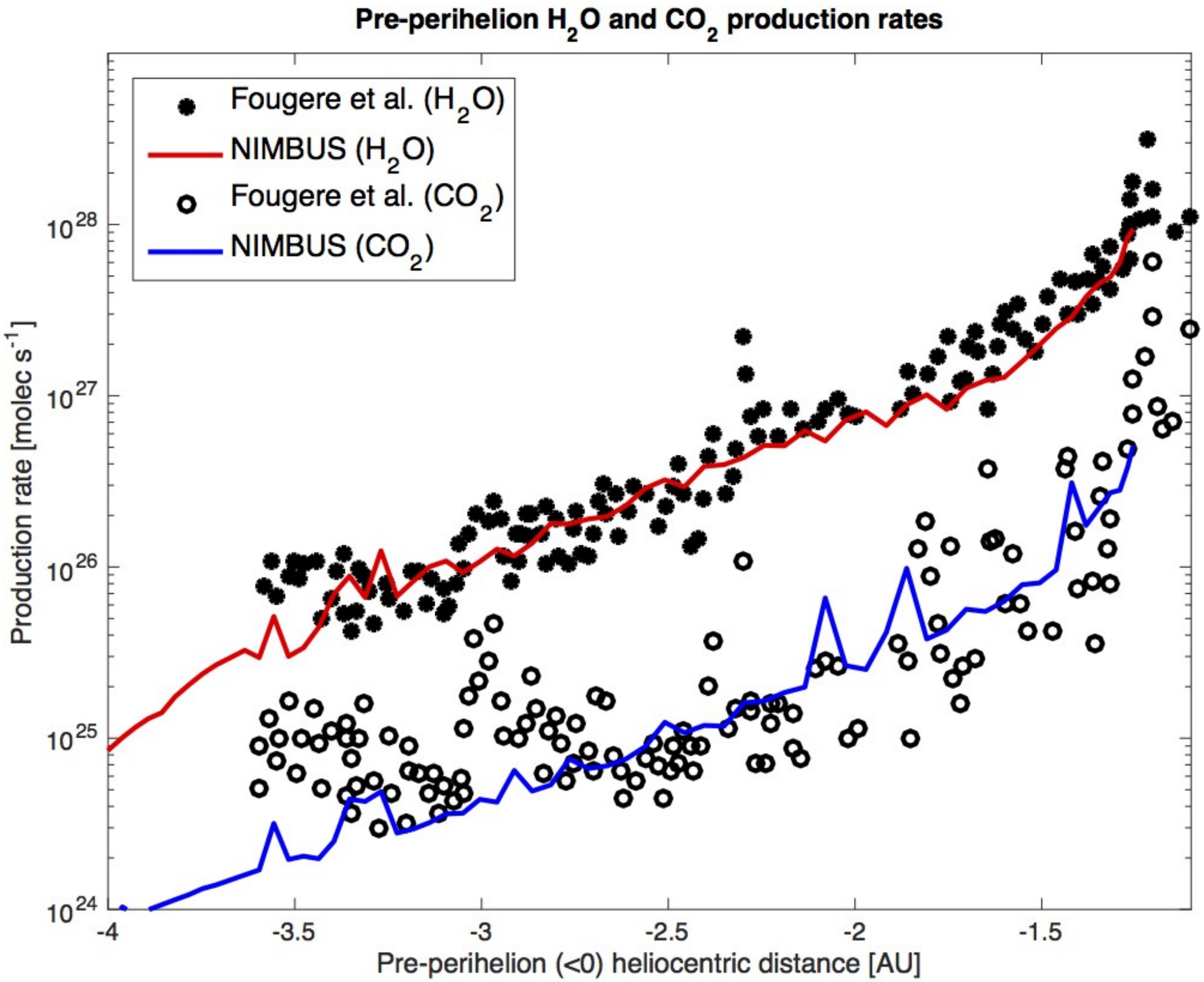


Lowering northern CO_2 abundance does not help (black/blue)

The depth of the CO_2 sublimation front in the north should be increased to at least 3.8 m

Image credits: Davidsson *et al.* In preparation.

Final solution



APHELION
INITIAL CONDITIONS

Dust/water-ice mass ratio:
South: d/i=1
North: d/i=2

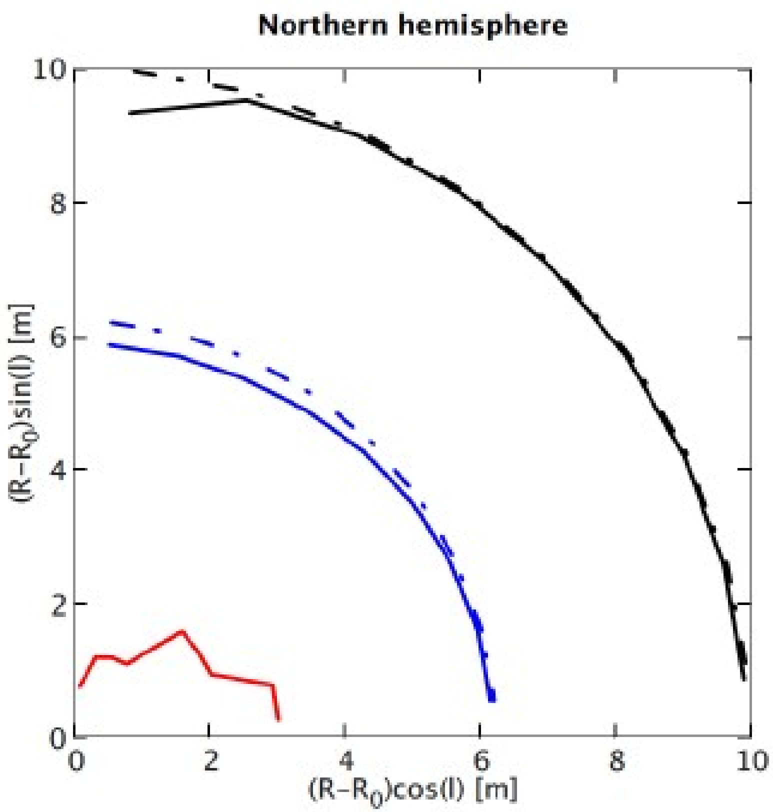
Northern deposits less ice-rich because material is aged

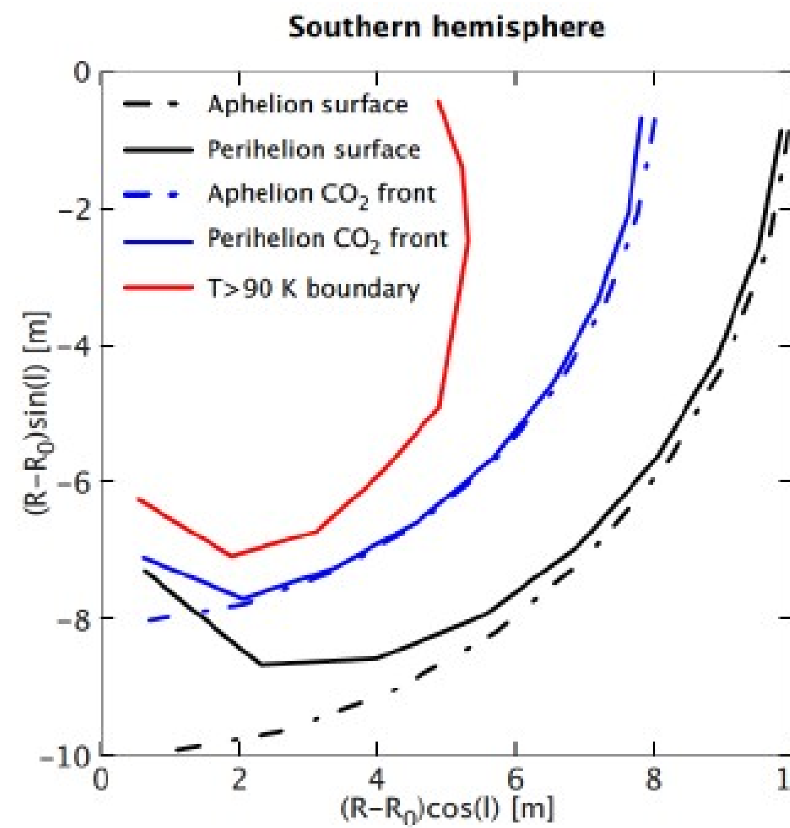
Carbon dioxide sublimation front:
South: d=0.9 m
North: d=3.8 m

Northern CO_2 is deeper: active for longer than south, covered by CO_2-poor airfall

Image credits: Davidsson *et al.* In preparation.

Conditions at perihelion





Black: amount of surface erosion approaches 3 meters near the south pole

Water sublimation front at perihelion: 0.4-4.8 cm below surface depending on latitude

CO2 sublimation front moves little; near south pole can be within ~0.2 m of the surface

Image credits: Davidsson *et al.* In preparation.

Conclusions

- Water ice a few mm-cm below the surface
  - Consistent with diurnal cycle of jets
- The interior is relatively water-rich
  - Coma d/i differs from that of nucleus because internal vapor diffuse both up (escape) and down (deep recondensation)
- Carbon dioxide ice at 0.2-2 m below the surface in the south
  - Local exposure, as observed by VIRTIS, likely
- Carbon dioxide ice at ~4 m below the surface in the north
  - The observed production rate cannot be matched without a substantial contribution from the north. Originates from underneath the airfall debris layer